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ELECTROACTIVE POLYMERS AS ARTIFICIAL MUSCLES - CAPABILITIES, POTENTIALS AND CHALLENGES

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INTRODUCTION

The low density and relative ease of shaping made polymers highly attractive for fracture critical applications such as aerospace. Polymer matrix composite materials significantly impacted the construction and capability of high performance aircraft. In recent years, the resilience characteristic of polymers has been exploited to support the emerging field of inflatable structures. Balloons were used to cushion the deployment of the Mars Pathfinder lander on July 4, 1997, paving the path for the recent large number of related initiatives. Inflatable structures are now being used to construct rovers (Figure 1), aerial vehicles, telescopes (Figure 2), radar antennas, and others. Some of these applications have reached space flight experiments, whereas others are now at advanced stages of development.

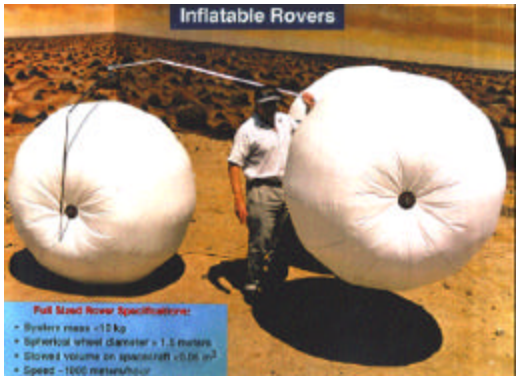


FIGURE 1: JPL rover using inflatable wheels.

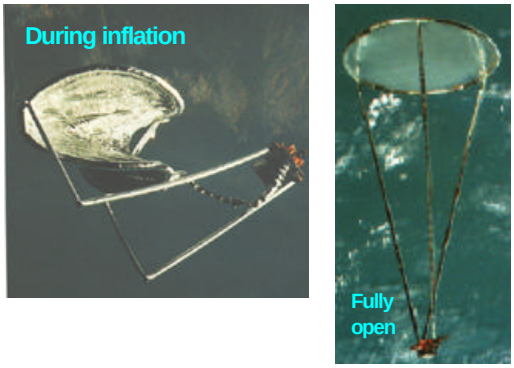


FIGURE 2: A Space Shuttle view of an inflatable structure experiment (May 1996).

The recent introduction of polymers that induce large strain under electrical activation led to their consideration as potential actuators. The level of induced strain can be as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Also, they are superior to shape memory alloys (SMA) in their spectral response, lower density, and resilience. Generally, EAP are electrically hard and mechanically soft. Particularly, ferroelectric polymers have a coercive field in the range of 100 MV/m, which is of the order of 100 times the coercive fields of ceramic ferroelectrics making polymers quite stable electrically. On the other hand, EAP materials reach their elastic limit at lower stress levels compared to EAC, and their actuation stress falls far shorter than EAC and SMA actuators. In Table 1 a comparison is given between EAP, EAC and SMA and it is easy to see the properties in which EAP offer superior capability.

The most attractive feature of EAPs is their ability to emulate biological muscles offering resilience, toughness, large actuation strain and inherent vibration damping. This similarity gained them the name "Artificial Muscles" with the potential of developing biologically inspired robots. Biomimetic robots actuated by EAP can be made highly maneuverable, noiseless and agile, with various shapes and they can enable to make science fiction ideas a faster reality than would be feasible with any other conventional actuation mechanisms. Unfortunately, at present the force actuation and mechanical energy density of

TABLE 1: Comparison of the properties of some actuation materials

Property	Electro-static silicone elastomer [Perline]	Polymer Electrostrictor [Zhang]	SMA	Single Crystal Electrostrictor [Park]	Single Crystal Magnetostrictor [Harhaway]
Actuation strain	32 %	4 %	8 %	1.7 %	2 %
Blocking Force/Area *	0.2 MPa	0.8 MPa	700 MPa	65 MPa	100 MPa
Reaction speed	µsec	µsec	sec to min	µsec	µsec
Density	1.5 g/cc	3 g/cc	6 g/cc	7.5 g/cc	9.2 g/cc
Drive field	144 V/µm	150 V/µm	--	12 V/µm	2500 Oe
Fracture toughness	large	large	large	low	large

*Note: Values were calculated assuming the elastic properties were independent of applied field and are therefore approximated.

EAPs are relatively low, limiting the potential applications that can be considered. In recognition of the need for international cooperation among the developers, users and potential sponsors, the author organized though SPIE International the first EAP Conference on March 1-2, 1999. This Conference was held in Newport Beach, California, USA and was the largest ever on this subject, making an important milestone, and turning the spotlight onto these emerging materials and their potential. Following this success, MRS conference was initiated to address the fundamental issues related to the material science of EAP. Further, the author established a homepage linking websites of worldwide EAP research and development facilities (http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm). Also, he initiated the publication of the WW-EAP Newsletter, which is published electronic (http://eis.jpl.nasa.gov/ndeaa/nasa-nde/newsltr/WW-EAP_Newsletter.PDF). He also helped establishing the WW-EAP Newsgroup.

The increased resources, the growth in number of investigators conducting EAP related research, and the improved collaboration among developers, users and sponsors are all expected to lead to rapid progress in the coming years. Recently, the author challenged the worldwide community of EAP experts to develop a robotic arm that is actuated by artificial muscles to win a wrestling match with a human opponent (Figure 3). Progress towards this goal will lead to great benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, leading to a "bionic human." A remarkable contribution of the EAP field would be to one day seeing a handicapped person jogging to the grocery store using this technology.

FIGURE 3: Grand challenge for the EAP community.

NEED FOR AN EFFECTIVE EAP INFRASTRUCTURE

Construction of mobility or articulation system that is actuated by EAP requires components as shown in Figure 4 as a block diagram. While each of the listed components is at various advanced research phases, EAP actuators are the least developed technology and extensive effort is required to bring it to a mature stage. Unfortunately, the EAP materials

that emerged so far are still exhibiting low force, are not effective and there are no commercially available robust materials for consideration in practical applications. In recent years, a series of EAP materials that induce large strain were documented, including carbon nanotubes, ferroelectric, electrostrictives, ion exchange membranes, conductives, electrostatics and piezoelectrics [Bar-Cohen, 1999a]. In order to be able to transition these materials from development phase to effective actuators there is a need to establish an adequate "EAP infra-structure". The author's view of this infrastructure and the areas needing simultaneous development are shown schematically in Figure 5. This involves the need for adequate understanding of EAP materials' behavior and the necessity to assure their durability in service. Enhancement of the actuation force requires knowledge of the basic principles using computational chemistry models, comprehensive material science, electro-mechanics analytical tools and improved materials processes. Efforts are needed to gain a better understanding of the parameters that control the EAP electro-activation force and deformation. The processes of synthesizing, fabricating, electroding, shaping and handling will need to be refined to maximize their actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to allow documenting the material properties to support design engineering towards making EAP the actuators of

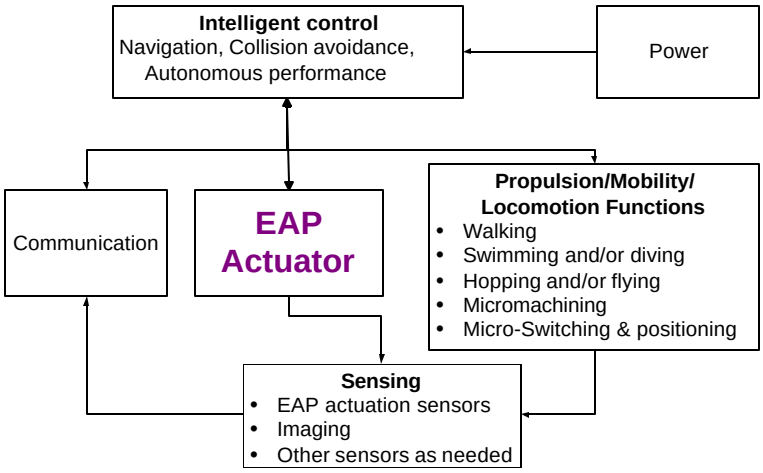


FIGURE 4: A schematic diagram of the basic components of an EAP-driven system.

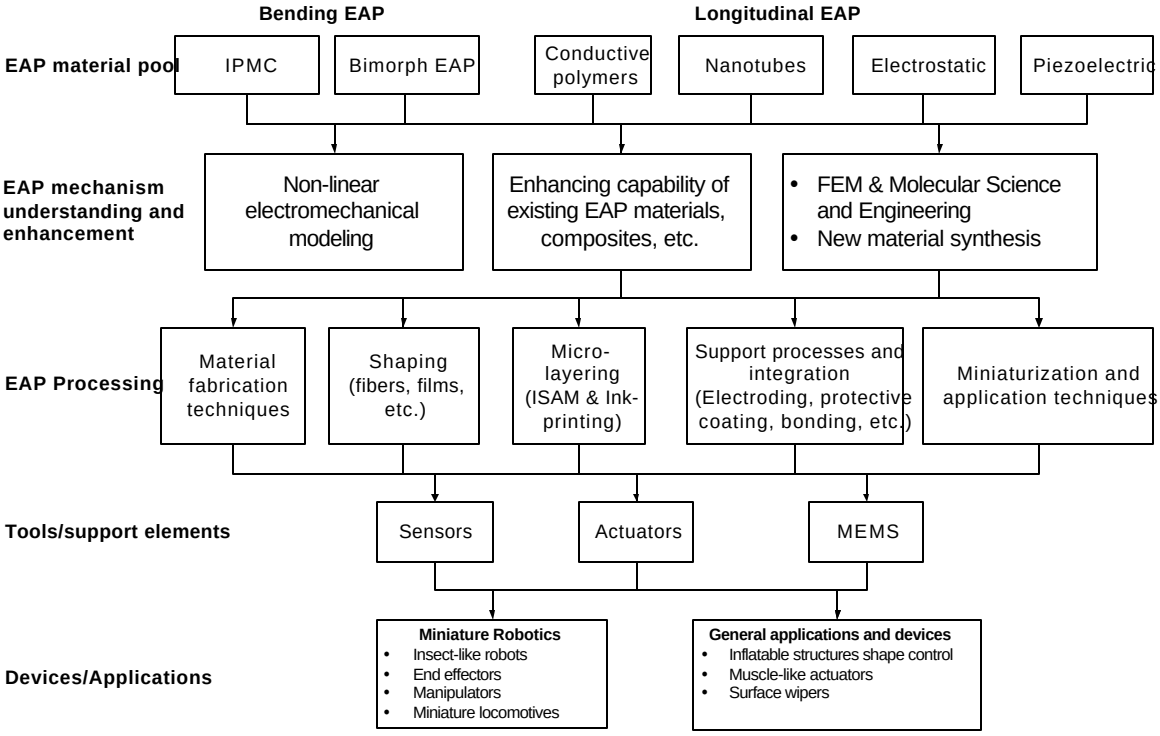


FIGURE 5: EAP infrastructure and areas needing attention.

choice. Various configurations of EAP actuators, sensors and potential MEMS will need to be studied and modeled to produce an arsenal of effective actuators. The development of the infrastructure is multidisciplinary and requires international collaboration.

BIOLOGICAL MUSCLES AND SCIENCE FICTION

Developing intelligent robots requires the combination of strong muscles (actuators) and acute sensors, as well as the understanding of the biological model. Using effective EAP materials as artificial muscles, one can develop biologically inspired robots and locomotives that can possibly walk, fly, hop, dig, swim and/or dive. Natural muscles are driven by a complex mechanism and are capable of lifting large loads at short (millisecond) response times. The performance characteristics of muscles are difficult to measure and most measurements were made on large shell-closing muscles of scallops. Peak stress of 150-300-KPa is developed at a strain of about 25%. Maximum power output is 150 to 225-W/kg; average power is about 50-W/kg with an energy density of 20-70-J/kg, which decreases with the increase in speed. Since muscle is fundamental to animal life and changes little between species, we can regard it as a highly optimized system. It is a system that depends on chemically driven reversible hydrogen bonding between two polymers, actin and myosin. Muscle cells are roughly cylindrical, with diameters between 10 and 100-μm and up to few centimeters long. Although muscles produce linear forces, motions at joints are all rotary. Therefore, the strength of an animal is not just muscle force, but muscle force as modified by the mechanical advantage of the joint [Alexander, 1988], which usually varies with joint rotation. The mechanical energy is provided by a chemical free energy of a reaction involving adenosine triphosphate (ATP) hydrolysis. The release of Ca+2 ions seems turning on and off the conformational changes associated with muscle striction.

Insects mobility is under extensive study and there is a relatively large body of knowledge in place, as for example at the University of California, Berkeley [Full and Tu, 1990]. A windmill was used with a photoelastic coating to study the details of insects walking mechanisms, where insects with various numbers of legs were investigated. Also, the size of electronic devices has become so small that insects can be instrumented to perform tasks once viewed as science fiction. At the University of Tokyo, Japan, a spider and other insects were instrumented as locomotives to carry backpacks of wireless electronics. Development of EAP actuators is expected to enable insect-like robots that can be launched into hidden areas of structures to perform inspection and various maintenance tasks. In future years, EAP may emulate the capabilities of terrestrial creatures with integrated multidisciplinary capabilities to launch space missions with innovative plots. Some biological functions that can be adapted include soft-landing like cats, traversing distances by hopping like a grasshopper and digging and operating cooperatively as ants.

CURRENTLY AVAILABLE EAP MATERIALS

The beginning of the field of EAP can be traced back to the milestone discovery of an electret when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field [Eguchi, 1925]. Generally, electrical excitation in only one of the mechanisms that can be used to induce elastic deformation in polymers [Perline, et al, 1998, and Zhang, et al, 1998]. Other activation mechanisms include chemical [Kuhn, et al, 1950; Steinberg, et al, 1966; and Otero, et al, 1995], thermal [Tobushi, et al, 1992; and Li, et al, 1999], magnetic [Zrinyi, et al, 1997], and optical [van der Veen & Prins, 1971]. Polymers that are chemically stimulated were discovered before half a century when collagen filaments were demonstrated to reversibly contract or expand when dipped in acid or alkali aqueous solutions, respectively. Even though very little has since been done to exploit such 'chemo-mechanical' actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles. The convenience and the practicality of electrical stimulation and the technical

progress led to a continuously growing emphasis on EAP materials. Following the 1969 observation of a substantial piezoelectric activity in PVF2, investigators started to examine other polymer systems and a series of effective materials have emerged. While the list of such EAP has grown considerably, PVF2-TrFE is the only material that can be obtained commercially. Generally, EAP can be divided into two categories: Wet (ionic) and dry. The dry polymers (electrostrictive, electrostatic, piezoelectric and ferroelectric) require high activation voltage (>100-V/μm) that is close to the breakdown level. However, they can be made to hold DC voltage induced displacement allowing considerations for robotic applications. Also, these materials have a greater mechanical energy density. In contrast, wet EAP materials (Ion-exchange, conductive polymers, gels, etc.) require drive voltages as low as 1-2 Volts. However, there is a need to maintain their wetness and it is difficult to sustain DC-induced displacements. The induced displacement of both the dry and wet EAP can be either bending or stretching/contraction. Overall, any of the EAP material can be made to bend with a significant curving response, which appears appealing. However, such actuators have relatively limited potential applications due to the low force or torque that can be induced.

WET (IONIC) EAP

IONIC POLYMERS

Potentially, ionic polymers can be synthesized in a gel form to produce strong actuation, which may match the force and energy density of biological muscles. These materials are generally activated by a chemical reaction, where changing from an acid to base environment causes the gel to become dense or swollen, respectively. Researchers at the University of Arizona, USA [Calvert, et al, 1998] successfully stimulated this reaction electrically. They drove embedded electrodes, where the cathode side becomes more basic and the anode side more acidic to cause bending actuation. However, the response of this multilayered gel structure is relatively slow due to the need to diffuse ions through the gel. An expansion and shrinkage of a layered gel structure from 3x3-cm to 6x6-cm was demonstrated over a period of 20-min. This reaction is far from being practical and is further hampered by the fact that the induced large displacement causes damage to the electrode leading to failure of the actuator after 23 activation cycles. Current efforts are directed towards the use of thin layers and more robust electroding techniques.

Generally, ionic polymers can be made to swell under electrical activation when the materials contain solvated ions. This type of polymers are conductive and an electrophoresis or electro-osmotic drag mechanisms is inducing conformational changes. Swelling of the polymer can occur as a result of sorption of solvents (usually water) even in the absence of applied electric field. Electrochemical reactions (oxidation/reduction) occur at the electrodes that either promote or hinder the actuation mechanism. Most reported actuators that use ionic polymers exploit the voltage controlled swelling to form bending. The required voltage may vary from 1-mV to 50-V and the response time depends on thickness, diffusion, and kinetics of electrochemical reactions. The reaction rate of this type of EAP materials can vary from milliseconds to minutes. Protective coating, which acts as artificial skin, needs to be developed to practically operate these EAP materials in dry environments. The use of polar low-vapor-pressure solvents (such as propylene carbonate) can help enhancing the ability of ionic polymers to operate at harsh conditions. Some of the known ionic conductive polymers include: Polypyrrole, Polyethylenedioxythiophene, Poly(p-phenylene vinylene)s, Polyaniline, and Polythiophenes. Among this group, Pdypyrrole was demonstrated to have the highest electromechanical response [Otero, et al, 1995] but at the present stage their actuation force is still relatively low, measured in grams or less.

The mechanism that is responsible for the chemo-mechanical behavior of ionic gels under electrical excitation is described by [Gong, et al, 1991; Osada, et al, 1992, Osada & Matsuda, 1995; and Osada & Ross-Murphy, 1993] and a model for hydro-gel behavior as contractile EAP is described in [Gong, et al, 1994]. Significant amount of research and development as well as applications using ionic gel polymers were investigated at the Hokkaido University, Japan. These include electrically induced vending of gels [Osada & Hasebe, 1985] and electrical induced reversible volume change of gel particles [Osada & Kishi, 1989].

IONIC POLYMER METALLIC COMPOSITE (IPMC)

Perfluorinated ion exchange membrane platinum composite (IMPC) with metallic electrodes deposited on both sides is a bending EAP material. Two types of base polymers are used to form IPMC: Nafion® (perfluorosulfonate made by DuPont) and Flemion® (perfluorocaboxylate, made by Asahi Glass, Japan). The chemical structure of Nation® is shown in Figure 6. Prior to using these base polymers, they were widely employed in fuel cells and production of hydrogen (hydrolysis). The operation as actuators is the reverse process of the charge storage mechanism associated with fuel cells. A relatively low voltage is required to stimulate bending in IPMC, where the base polymer provides channels for mobility of positive ions in a fixed network of negative ions on interconnected clusters. Since the author has been involved extensively with research related to this type of EAP [Bar-Cohen, et al, 1998], a greater attention will be given herein to this type of EAP. In 1992, IPMC was realized to have EAP characteristics by three groups of researchers [Oguro, et al, 1992] in Japan, and by [Shahinpoor, 1992] and [Sadeghipour, *et al*, 1992] in the United States. In order to chemically electrode IPMC films, metal ions (Platinum, gold or others) are dispersed throughout the hydrophilic regions of the polymer, and are subsequently reduced to the corresponding zero-valence metal atoms. Generally, the ionic content of the IPMC is an important factor in the electromechanical response of these materials. Bending results for sodium cations and platinum metallization are shown in Figures 7, where using low voltage (1-10 Volts) large displacement is observed at frequencies below 1-Hz and significantly decreases with frequency. In recent years, this capability was enhanced using Li+, tetra-n-butylammonium and other types of cations with gold metallization [Yoshiko, et al, 1998; and Oguro, et al, 1999].

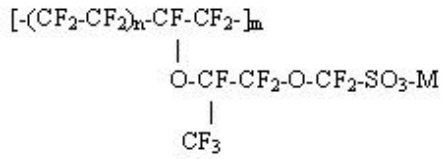


FIGURE 6: Nafion® chemical structure (Where n ~ 6.5, 100 < m < 1000, and M^+ is the counter ion (H^+, Li^+, Na^+ or others).

The structure and properties of the IMPC have been the subject of numerous investigations (see for example [Heitner-Wirguin, 1996]). While its operation mechanism is still not clear, methodic modeling and characterization of the material behavior is significantly improved the understanding. Diffusion and coulomb forces are considered as the driving mechanisms responsible for the bending and the associated reverse effects [Nemat-Naser et al, 2000]. One of the interesting properties of IPMC is its ability to absorb large amounts of polar solvents, i.e. water. When equilibrated with aqueous solutions, the polymer membrane swells to absorb certain amount of water. Swelling equilibrium results from the balance between the elastic forces of the polymeric matrix and the water affinity to the fixed ion-exchanging sites and the moving counter ions. The mechanism of

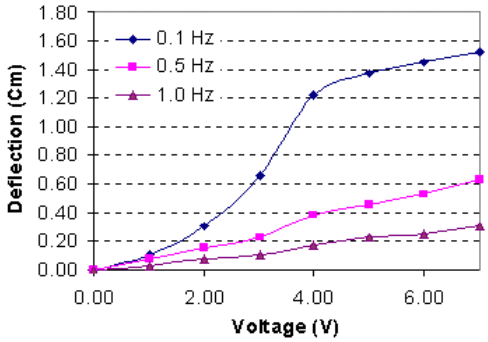


Figure 7: Typical response of Na+/Pt IPMC at various voltage levels and 3 frequencies.

bending is partially related to migration of mobile ions within the networks caused by an applied electric field.

IPMC was found to respond at temperatures as low as -100°C where an increase in voltage allows compensating for the loss in efficiency. This result paved the path for considering IMPC as an actuator for space mechanisms as will be discussed later in this manuscript. However, under DC activation the material bends relatively quickly, 0.1 to 1-sec (depending on the size of the cations) followed by a slow recoiling with a permanent deformation. The recoiling can be as serious as bending in the opposite direction of the activating voltage, as in the case of Na+ cations. The author and his colleagues investigated the issues that affect the application of IPMC as an actuator and identified a series of challenges. The challenges and the solutions that were determined are listed in Table 2. As can be seen from the table, most of the challenges can be met with an acceptable solution except for three: the need to protect the material from drying, the excitation of electrolysis at voltages above 1.03 Volts and the induced permanent deformation. Unless these issues are effectively addressed the use of IPMC for practical applications will be hampered.

TABLE 2: Challenges and identified solutions for issues regarding the application of IPMC.

Challenge	Solution
Fluorinate base - difficult to bond	Apply pre-etching
Sensitive to dehydration	Apply protective coating over pre-etched IPMC
Off-axis bending actuation	Constrain the free end
Electrolysis occurs at >1.03-V	Use efficient IPMC requiring lower actuation voltage
Operate at low temperatures	IPMC was demonstrated to operate at -140°C
Remove small size dust	Use effective wiper-blade design and high bias voltage
Reverse bending under DC voltage	Limit application to dynamic operations
Protective coating is permeable	Develop alternative coating possibly using overcoat
Residual deformation No established quality assurance	Still a challenge Use short beam/film and tackle the critical issues

Ineffective protective coating: Since the actuation capability of IPMC is attributed to its ionic content, it is necessary to continuously maintain its moisture. A protective coating was developed to serve as the equivalence of a biological skin, and it was demonstrated to effectively maintain the moisture for several months [Bar-Cohen, et al, 1998]. Unfortunately, this silicone base coating was found to be too permeable and therefore would not be effective for long term operation of the IPMC in dry conditions. Efforts are underway to identify a better coating technique.

Electrolysis: Voltages at levels above 1.03-V involve electrolysis during electro-activation causing degradation, heat and release of gasses. This issue raises a great concern since the emitted hydrogen accumulates under the protective coating and generates blistering that would rupture the coating, particularly in high vacuum environment as in space. The use of tetra-n-butylammonium cations was shown to provide higher actuation efficiency allowing to reduce the needed voltage and to minimizing the electrolysis effect. However, large bending requires voltages at significantly higher level than the 1.03-V limit.

Permanent deformation under DC activation: Unfortunately, under DC voltage IPMC does not maintain the induced bending and it retracts after several seconds. Further, upon removal of the electric field an overshoot bending occurs in the opposite direction moving slowly towards the steady state position leaving a permanent deformation. This issue was not resolved yet and is hampering the application of IPMC.

CARBON NANOTUBES

Nanotubes are relatively new EAP materials, which have immerged in 1999 [Baughman, 1999]. They are composed of carbon nanotubes having diamond-like mechanical properties. Considering the mechanical strength and modulus of the individual carbon nanotubes and the achievable actuator displacements, this actuator has the potential of providing higher work per cycle than previous actuator technologies and of generating much higher mechanical stresses. Further, since carbon offers high thermal stability, carbon nanotubes may eventually be used at temperatures exceeding 1000 °C, which far exceeds the capabilities of alternative high-performance actuator materials. The material consists of nanometer size tubes and it was shown to induce stains at the range of 1% along the length. The key obstacle to the commercialization of this EAP is it high cost and the difficulty to mass-produce. A carbon nanotube actuator can be constructed in about by laminating together two narrow strips cut from a carbon nanotube sheet, using an intermediate adhesive layer, which is electronically insulated. The resulting "cantilever device" is immersed in an electrolyte, such as a sodium chloride solution, and an electrical connection is made to the two formed nanotube strips. The application of about a volt bends the actuator in one direction, and reversing the potential bends the actuator in the opposite direction.

DRY EAP
FERROELECTRIC POLYMERS

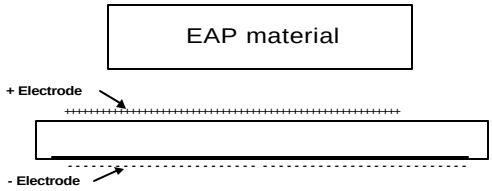
Poly(vinylidene fluoride), also known as PVDF or PVF2, and its copolymers are the most widely exploited ferroelectric polymers. These polymers are partly crystalline with an inactive amorphous phase having relatively high Young's moduli near 1-10 GPa. This relatively high elastic modulus offers high mechanical energy density when using EAP based on this type of materials. A large applied AC field (~200 MV/m) can induce electrostrictive (nonlinear) strains of nearly 2%. However this level of field is dangerously close to dielectric breakdown, and the dielectric hysteresis (loss, heating) is very large. Scheinbeim and his coinvestigators [Sen, 1984] investigated the effect of heavy plasticization (~65 wt. %) of ferroelectric polymers hoping to achieve large strains at reasonable applied fields. However, the plasticizer is also amorphous and inactive, resulting in decreased Young's modulus, permittivity and electrostrictive strains. Recently, Zhang [1998] has introduced defects into the crystalline structure using electron radiation to reduce the dielectric loss dramatically in P(VDF-TrFE) copolymer. This permits AC switching with a lot less generated heat. As large as 5% electrostrictive strains can be achieved at low frequency drive fields with amplitudes of about 150 V/μm.

As with ceramic ferroelectrics, electrostriction can be considered as the origin of piezoelectricity in ferroelectric polymers [Furukawa, 1990]. A DC bias polarization can either be present via a *poling* process introduced before making a device, in which case a remnant polarization persists, or large DC electric field is applied during operation of the material as a device. In the latter case, no remnant polarization is observed when the bias is removed and, as a ferroelectric material, a very small hysteresis is observed in the polarization-electric field loop. Unlike electrostriction, piezoelectricity is a linear effect, where not only will the material strain when voltage is applied, but a voltage signal will be induced when a stress is applied. This enables them to be used as sensors and sonars. Care must be given to not apply too large of applied voltage, mechanical stress, or high temperature for fear of de-poling the material.

ELECTRO-STATICALLY STRICTED POLYMER (ESSP) ACTUATORS

Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field. This characteristic allows producing longitudinal actuators that operate similarly to biological muscles using Coulomb

forces between electrodes to squeeze and thus stretch the material laterally. Longitudinal electrostatic actuators can be made of dielectric elastomer films and flexible electrodes [Perline, et al, 1998]. For this purpose, two silicone layers can be used with carbon electrodes on both sides of one of the layers, where the layers are wrapped to form a rope actuator (see Figure 8). Besides using ESSP in the form of ropes mimicking human muscle, bending actuators can be constructed by adding a passive backing layer on one side of the EAP film. ESSP actuators are subject to a major concern associated with the required large electric fields (~100 V/μm) necessary to induce significant strains (10-200%). The actuator has to be thin (<50μm) to assure the use of reasonable voltages. Overall, the associated voltages are close to the breakdown strength of the material and a safety factor needs to be used thus lowering its potential. Moreover, the relatively small breakdown strength of air (2-3 V/μm) presents additional challenge. The longitudinal actuation of the rope is the result of Poisson effect of squeezing the film resulting a lateral stretch and forming a significant displacement requires longer actuator. Elastomers with Young's moduli on the order of < 20 MPa and relative permittivity of 3 can induce large strain at the level of 30%. The Young's modulus is fairly temperature independent until the glass transition temperature is reached, at which point a sharp increase in the modulus occurs making the material too stiff to be used as electrostatic actuator.



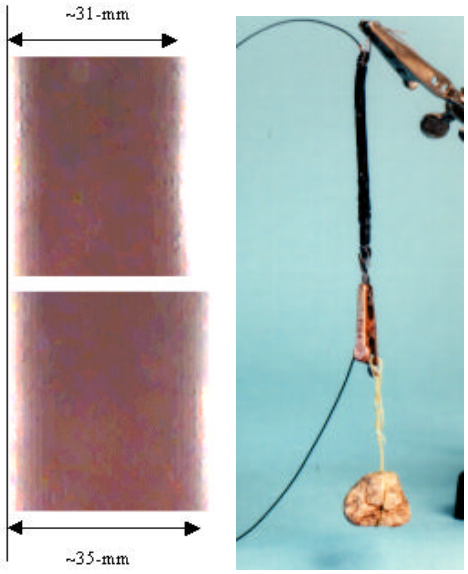


Figure 9: Left: Under electro-activation, an EAP film with electrodes on both surfaces expands laterally. Middle: EAP film subjected to 25 V/μm induced over 12% extension. Right: ~15-g rock mounted at the end of an ESSP rope is electrically lifted and dropped.

ELECTRO-VISCOELEASTIC ELASTOMERS

Electro-viscoelastic elastomers represent another family of electroactive polymers. These EAP materials are composites of silicone elastomer and a polar phase. Before crosslinking, in the uncured state, they behave as electro-rheological fluids. An electric field is applied during curing to orient and fix in position the polar phase in the elastomeric matrix. These materials then remain in the "solid" state but have a shear modulus (both real and imaginary parts) that changes with applied electric field (< 6 V/μm) [Shiga, 1997]. A stronger magneto-rheological effect can also be introduced in an analogous manner and as much as a 50% change in the shear modulus can be induced [Davis, 1999]. These materials may be used as alternatives to electrorheological fluids for active damping applications. These type of EAP can be used to perform active damping is support of precision control of robotic arms with a closed-loop system.

DEVELOPMENT OF EAP FOR SPACE APPLICATIONS

Since 1995, under the author's lead, planetary applications using EAP have been explored while improving the understanding, practicality and robustness of these materials. EAP materials are being sought as a substitute to conventional actuators, such as motors, gears, bearings, screws, etc. [Bar-Cohen, et al, 1999b]. Generally, space applications are the most demanding in terms of operating conditions, robustness and durability offering an enormous challenge and great potential for these materials. Under this NASA funded effort, ESSP and IPMC were used to produce longitudinal and bending actuators, where a dust-wiper, gripper and robotic arm were demonstrated. The development of a dust-wiper (Figure 10) have received the most attention and it was considered for the Nanorover's optical/IR window, which is part of the MUSES-CN mission. The MUSES-CN is a joint NASA and the NASDA (National Space Development Agency of Japan) mission scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid. The use of IPMC was investigated jointly with NASA LaRC, USA, and Osaka National Research Institute and Kobe University from Japan. The team used perfluorocarboxylate-gold composite with two types of cations, tetra-n-butylammonium and lithium. The IPMC was used as the actuator that wipes the window with a unique 104-mg blade having fiberglass brush, which was developed by ESLI (San Diego, CA). This blade is subjected to high voltage (~1.5-KV) to repel dust and thus augmenting the brushing mechanism provided by the blade. Unfortunately, the critical issues that affect the application of IPMC hampered the consideration of launching the dust-wiper in this mission.

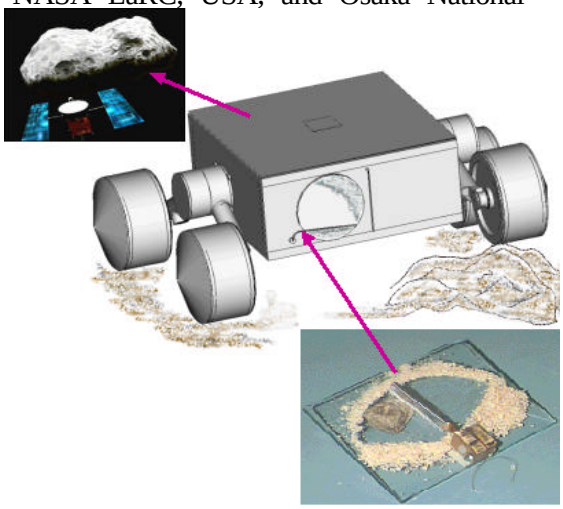


FIGURE 10: Schematic view of the EAP dust-wiper on the MUSES-CN's Nanorover (right) and a photograph of a prototype EAP dust-wiper (left).

Another application of EAP actuators, having even lower technology readiness, which was considered, is the development of a miniature robotic arm (Figure 11 and 12). An ESSP actuator was used to lift and drop the arm, whereas a 4-finger IPMC gripper was used to grab rocks and other objects. When grabbing rocks, the four fingers operate much like a human hand (see Figure 12).

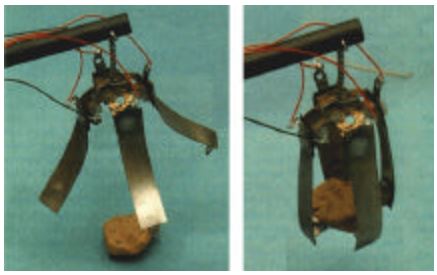


FIGURE 11: 4-finger EAP gripper lifting a rock much like a human hand.

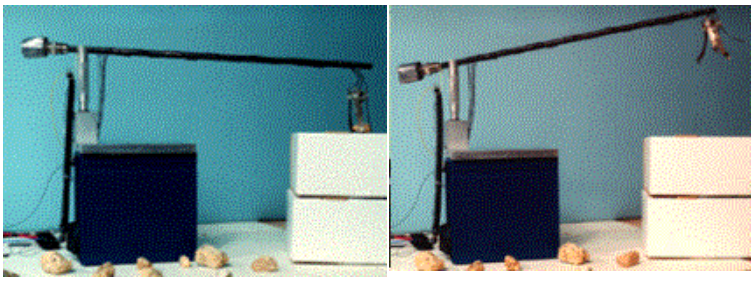


FIGURE 12: A miniature robotic arm using EAP actuators to provide the lifting/dropping of the arm and manipulate the gripper fingers.

CONCLUDING REMARKS

In recent years, electroactive polymers have emerged with great potential to enable unique mechanisms, which can emulate biological systems. A series of materials were reported to induce large longitudinal and bending actuation. Efforts to apply such materials to

space applications revealed critical challenges that cannot be address with current technology. Much more research and development work still needs to be done before EAP will become the actuators of choice. The development of an effective infrastructure for this field is critical to the commercial availability of robust EAP actuators for practical applications. The challenges are enormous, but the recent international trend towards more cooperation, the greater visibility of the field and the surge in funding related research are offering great hope for the future of these exciting materials. The potential to operate biologically inspired mechanisms driven by EAP as artificial muscles is offering capabilities that are currently considered science fiction. To highlight this potential, the EAP science and engineering community was challenged to develop a robotic hand actuated by EAP that would win an arm-wrestling match against human opponent. Progress towards this goal will lead to great benefits to mankind particularly in the medical area including effective prosthetics.

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